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Behavior of Soil–Fly Ash–Lime Blends Under Different Curing Temperatures

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Abstract

Compaction of layers of soil–fly ash–lime blends is often used to improve soil conditions for infrastructure projects. Such understanding is the starting point to develop more rational dosages that allow for a more efficient use of resources. To achieve this objective the present research aims to quantify the influence of curing temperature (T), amount of lime (L), porosity (η), and porosity/lime ratio (η/L_{iv}) on the assessment of splitting tensile strength (q_t) and unconfined compressive strength (q_u) of sand–coal fly ash–lime blends. A series of splitting tensile and unconfined compression tests were carried out in the present work. The results show a linear function fits well the relation between q_t and qu with L, and a power function fits well as the relation between q_t and q_u with η for all curing temperatures of the specimens. It was also shown that the porosity/lime ratio (η/L_{iv}) is a good parameter in the evaluation of q_t and q_u of the studied blends for the whole range of lime, porosities and temperature studied, at specific amount of coal fly ash (25%) and curing time period (28 days). The volumetric cementitious material content (L_{iv}) is adjusted by an exponent (0.30 for all curing temperatures blends) to end in unique correlations for each temperature. For the sand, coal fly ash, lime, curing time period and curing temperatures, a unique relationship was achieved linking q_t as well q_u to η; L_{iv} and T. For a given curing time period (28 days), the relations q_t-η/L_{iv} and q_u-η/L_{iv} versus T are shown to vary linearly up to a threshold, when asymptotes occur. Finally, the relation between q_t/q_u is a constant and equal to 0.19 for the whole range of L, η and T studied.

Keywords: Temperature, porosity, lime, splitting tensile strength, unconfined compressive strength

1 Introduction

Improvement of local soils is usually necessary to meet the mechanical requirements of infrastructure projects such as foundations and subgrades of roads. Soil–fly ash–lime blends are often used for such improvement particularly as compacted layers over low bearing capacity soils (Thomé et

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al. 2005, Consoli et al. 2008) and as pavement layers (Cetin et al.2010). Although there are no dosage methodologies based on rational criteria considering the effect of different variables (e.g., amount of lime, porosity) and the effect of local climate (e.g., temperature).The first rational dosage methodology for soil-fly ash-lime was developed by Consoli et al. (2011a) considering the porosity/lime ratio (η/L_{iv}), defined by the porosity of the compacted mixture divided by the volumetric lime content, as an appropriate parameter to evaluate the unconfined compressive strength (q_u) of soil-fly ash-lime mixtures. On the other hand, even though it is already recognized by previous studies (e.g., Rojas and Cabrera 2001, 2002; Consoli et al. 2001; Al-Mukhtar et al. 2010a, b) that strength of soil-fly ash-lime mixes (based on pozzolanic reactions) is dependent on temperature (T), which acts as a catalyzer of pozzolanic reactions. It is still unknown if the effect of curing temperature should be inserted in a rational methodology. So, this study aims at approaching this issue by quantifying the influence of T, L, η and adjusted η/L_{iv} on q_t, q_u and q_t/q_u of a sand-fly ash-lime blend.

2 Experimental Program

The experimental program was carried out in three parts: geotechnical characterization, splitting tensile tests and unconfined compression tests.

2.1 Materials

The soil used in this study was rounded wind transported sand (named Osorio sand). The sample was collected in a disturbed state, by manual excavation. The results of the characterization tests are shown in Table 1. This soil is classified as uniform fine sand (SP) according to the Unified Soil Classification System.

The fly ash (FA) selected [type F according to ASTM C 618] was a residue of burning coal in a thermal power station, located near Porto Alegre. The main characteristic of Class F fly ash is the amount of calcium oxide (CaO) in the ash, which is typically less than 12% (in the present case CaO percentage is 0.8%). The results of the FA characterization tests are presented in Table 1. The FA is classified sandy silt (ML) according to the Unified Soil Classification System. A chemical analysis has shown that the fly ash is 65.2% SiO_2, 23.3% Al_2O_3 and 6.1% Fe_2O_3. X-ray diffraction showed that the material is composed predominantly by amorphous minerals. Insertion of fly ash in the mixture increases availability of alumina and silica from amorphous minerals (which promptly solubilize under high pH due to lime addition), growing reactions with lime and consequently increasing strength. Dry hydrated lime [$Ca(OH)_2$] was used throughout the whole study. The specific gravity of the lime grains is 2.49. Distilled water was used both for molding specimens for the tensile tests and for the characterization tests.

PROPERTIES	Osorio sand	Fly Ash
Specific Gravity	2.63	2.28
Medium Sand (0.2 mm < diameter < 0.6 mm)	-	1.00%
Fine Sand (0.06 mm < diameter < 0.2 mm)	100.00%	13.60%
Silt (0.002 mm < diameter < 0.06 mm)	-	84.90%
Clay (diameter < 0.002 mm)	-	0.50%
Effective Diameter (D50)	0.16 mm	0.018 mm

Table 1- Physical properties of Osorio sand and coal fly ash samples

2.2 Method

2.2.1.Program of Splitting Tensile and Unconfined Compression Tests

The splitting tensile and unconfined compression tests carried out under distinct curing temperatures constituted in such a way as to evaluate, separately, the influences of the curing temperature, lime content, porosity and porosity/lime ratio on the mechanical strength of the soil–coal fly ash–lime blends. Three different dry densities (14, 15, and 16 kN/m^3) were chosen after standard Proctor compaction test results carried out by Silvani (2013) presenting maximum dry density (γ_{dmax}) of 16 kN/m^3 at optimum moisture content (ω_{opt}) of 14%;three different lime percentages (calculated based on the mass of dry soil): 3, 5, and 7% were chosen following international and Brazilian experience (Consoli et al. 2001, 2011a, b) and 28 days of curing (minimum curing time for such blends when used as base of roads in Brazil—Consoli et al. 2001, 2011a) at temperatures of 20, 27.5, 35, and 50°C for tensile and 20, 35 and 50ºC for compression. Because of the typical scatter of data for the strength tests, a minimum of three specimens (for both tensile and compression) were tested for each point.

2.2.2.Molding and Curing of Specimens

For the splitting tensile and unconfined compression tests, cylindrical specimens, 50 mm in diameter and 100-mm high, were used. The compacted sand-fly ash-lime specimens used in the tests were prepared by weighing dry Osorio sand, fly ash and lime, followed by hand-mixing the materials for approximately 5 min to a uniform consistency. The water [the moisture content of all specimens molded was approximately 14%, which is in accordance with optimum moisture content after standard Proctor compaction test results carried out by Silvani (2013)] was then added, continuing the mixing process for another 5 min until a homogeneous paste was created.

The amount of fly ash used in this work (25%) was calculated based on the mass of dry soil. The amount of lime for each mixture (varying from 3 to 7%) was calculated based on the mass of dry sand plus the mass of fly ash. The porosity of a sand-fly ash-lime specimen is a function of the specific gravity of sand grains (G_{ss}), and of the fly ash grains (G_{sFA})and the lime (G_{sL}), and can be calculated according to Eq. (1)(Consoli et al. 2011a):

$$\eta = 100 - \frac{100\left(\left(\frac{\left(\frac{\gamma_d V_s}{\left[1+\left(\frac{L}{100}\right)\right]}\right)\left(\frac{S}{100}\right)}{Gs_S}\right)+\left(\frac{\left(\frac{\gamma_d V_s}{\left[1+\left(\frac{L}{100}\right)\right]}\right)\left(\frac{FA}{100}\right)}{Gs_{FA}}\right)+\left(\frac{\left(\frac{\gamma_d V_s}{\left[1+\frac{L}{100}\right]}\right)\left(\frac{L}{100}\right)}{Gs_L}\right)\right)}{V_s} \qquad \text{Eq.(1)}$$

where: η = porosity of the sand-fly ash-lime specimen, FA = coal fly ash content (percentage of dry weight of sand), L = lime content (percentage of dry weight of soil plus fly ash), γ_d = dry density of the specimen and V_s = volume of specimen.

After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. Two small portions of the mixture were also taken for moisture content determination. The specimen was then statically compacted in three layers inside a cylindrical split mold, which was lubricated, so that each layer reached the specified dry density. The top of the first and the second layers was slightly scarified. After the molding process, the specimen was immediately extracted from the split mold, and its weight, diameter and height measured with accuracies of approximately 0.01 g and 0.1 mm. The samples were then placed within plastic bags to avoid significant variations of moisture content.

They were cured in a humid room at four distinct temperatures and relative humidity above 95% for 28 days of curing days. The samples were considered suitable for testing if they met the following tolerances: Dry Density (γ_d): degree of compaction between 99 and 101% (the degree of compaction being defined as the value obtained in the molding process divided by the target value of γ_d); Moisture Content (ω): within 0.5% of the target value and Dimensions: diameter to within 0.5 mm and height 1 mm.

2.2.3. Splitting Tensile Tests and Unconfined Compression Tests

Splitting tensile tests followed Brazilian standard NBR 7222 (ABNT 1983), which is in accordance with standard ASTM C496 (ASTM 2011). Unconfined compression usually followed Brazilian standard NBR 5739 (ABNT 1980), which is in accordance with standard ASTM C39 (ASTM 2012). An automatic loading machine with maximum capacity of 50 kN and a proving ring with capacity of 10 kN and resolution of 0.005 kN were used for the both tests. After curing in the humid room, the specimens were submerged in a water tank for 24 h for saturation to minimize suction (Consoli et al. 2011a). Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. Then, the cylindrical specimen is placed horizontally between the platens of the compression-testing machine to the splitting tensile tests. The specimen is compressed by loading it along two opposite generatrices leading to failure in tension along the diameter contained in the plane formed by these two generators (the maximum load is recorded). The specimen is placed vertically between the platens of the compression-testing machine to the unconfined compression test and maximum load is recorded.

3 Results

3.1 Effect of the Porosity and Lime Content

Figs. 1 and 2 show, for a curing time period of 28 days, how lime amount and porosity affect the splitting tensile [Figs. 1(a and b)] and unconfined compressive [Figs. 2(a and b)] strength of the sand-fly ash-lime mixtures a curing temperature of 35°C. A linear function and a power function fit well the relations between strength and lime content and strength and porosity (η) for all lime contents, porosities, and temperatures studied. Both tensile and compressive strengths increase with increasing amount of lime and with reduction in porosity. An interesting feature that can be seen in Figs. 1a and 2a is the increase in the rate of strength gain with lime content, represented by the gradient of the fitted line, with the increase of the dry density. In present study, a reduction of porosity from approximately 46 to 38% conduces to an increase of approximately 100% of both tensile and compressive strengths. The mechanism by which the reduction in porosity influences the sand-fly ash-lime strength is related to the existence of a larger number of contacts.

Regarding temperature increase, current results have presented similar trends as obtained by Al-Mukhtar et al. (2010a, b) in lime— clay blends, which presented a considerably higher rate of strength increase for specimens cured at higher temperatures, confirming that temperature acts as a catalyzer of pozzolanic reactions.

3.2 Effect of Porosity/Lime Ratio

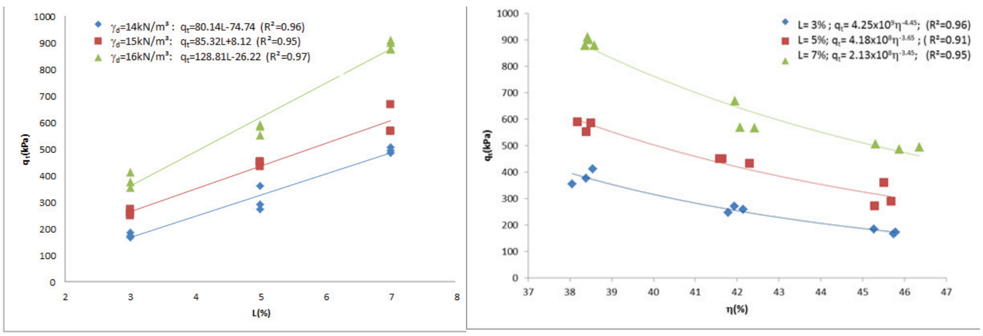
Rising values of porosity cause reduction of q_t and q_u whereas increasing lime content leads to larger values of q_t and q_u. Consoli et al. (2012) have proposed, specifically for soil-lime blends, the existence of explicit relations between q_t and q_u with η/L_{iv} [expressed as porosity (η) divided by the volumetric lime content (L_{iv}), the first stated as the volume of voids divided by total volume of specimen and the latter expressed as volume of lime regarding total volume of specimen], as defined by Eq. (2):

$$\frac{\eta}{L_{iv}} = \frac{\left(\frac{V_v}{V_{total}}\right)}{\left(\frac{V_L}{V_{total}}\right)} = \frac{V_v}{V_L} \qquad \text{Eq.(2)}$$

where V_v is the volume of voids (water + air) of the specimen, V_L is the volume of lime of the specimen and V_{total} is the total volume of the specimen.

The reason for using porosity/lime ratio (η/L_{iv}) in the present research is based on the concept that water/lime ratio (defined as the water mass divided by the lime mass) was a useful parameter in the analysis of the strength development of cemented soils in which pores of the samples were predominantly water filled, so that the water content would reflect the amount of voids. In the present study, the voids are only partially filled by water, and there is no unique relationship between the voids and the amount of water. Therefore, for the soil lime in the unsaturated state, as is usual in geotechnical engineering practice, a relationship between porosity and volumetric lime content should be more appropriate in the analysis and control of its mechanical strength.

The relation q_t versus η/L_{iv} suggests that η/L_{iv} joins the distinct effects of both variables (η and L_{iv}) in a unique factor controlling q. From a mechanical standpoint, it indicates that although η and L_{iv} affect separately q_t, the negative effect on q_t of increasing values of porosities might be counteracted by increasing the volumetric lime content. Figs. 3(a and b) present splitting tensile strength and unconfined compressive strength, respectively, as a function of the porosity/lime ratio (η/L_{iv}), for specimens cured at a temperature of 35°C and 28 days of curing, distinguishing the plotted points by their lime contents. Points with similar η/L_{iv}, but obtained by different combinations of lime content and porosity, show distinct strengths for each lime content (similar results are obtained for other curing temperatures). It is supposed to be attributable to substantial differences in rates of change of both q_t and q_u with porosity (η) and with the inverse of the volumetric lime content ($1/L_{iv}$). Away to make the variation rates of η and $1/L_{iv}$ compatible is through the application of a power to one of them (in the present work the application of a power is suggested to be on L_{iv}—the optimum fit was found to be applying a power equal to 0.30 to the sand-fly ash-lime blends studied herein) as shown in Figs. 4(a and b), considering a curing temperature of 35°C. Similar results are obtained for other curing temperatures, as can be seen in Figs. 5(a and b), respectively, for q_t and q_u.



(a) (b)

Figure 1- Variation of splitting tensile strength (q_t) with: (a) lime content (L); (b) porosity for curing temperature of 35°C.

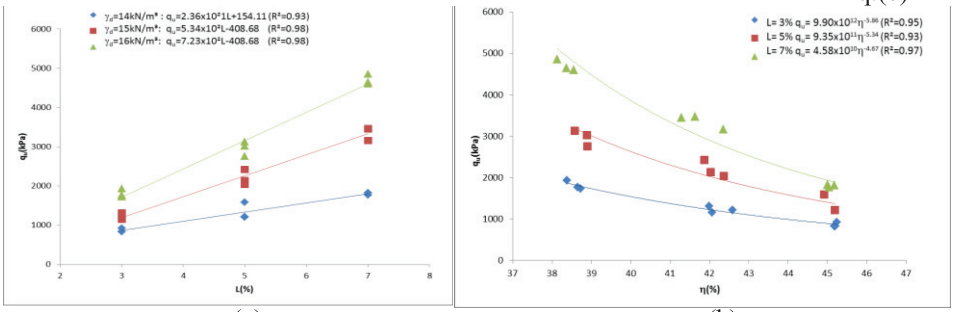
Coefficients of determination (R^2) of 0.86, 0.93, 0.95, and 0.91, respectively, for curing temperature of 20°C—Eq. (3), 27.5°C— Eq. (4), 35°C—Eq. (5), and 50°C—Eq. (6), can be observed in Fig. 5(a) between $\eta/(L_{iv})^{0.30}$ and the splitting tensile strength (q_t):

$$q_t(kPa) = 5.67x10^6\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \qquad \text{Eq.(3)}$$

$$q_t(kPa) = 9.12x10^6\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad \text{Eq.(4)}$$

$$q_t(kPa) = 13.1x10^6\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad \text{Eq.(5)}$$

$$q_t(kPa) = 13.4x10^6\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad \text{Eq.(6)}$$



(a) (b)

Figure 2-Variation of unconfined compressive strength (qu) with: (a) lime content (L); (b) porosity for curing temperature of 35°C

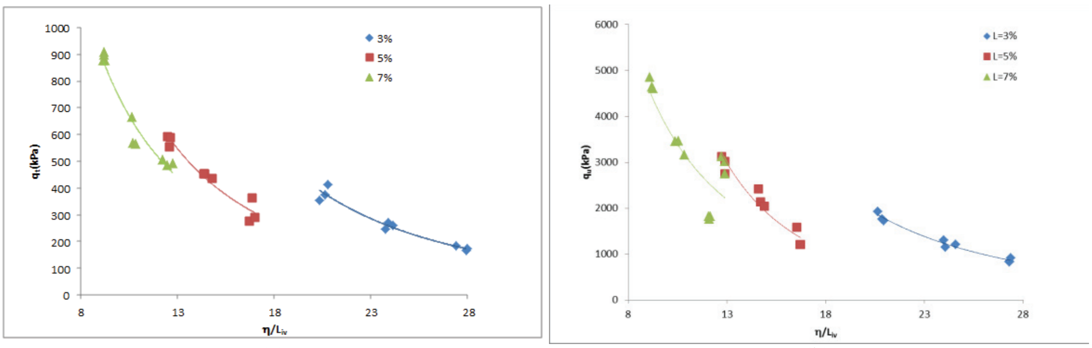
Coefficients of determination (R^2) of 0.75, 0.92, and 0.94, respectively, for curing temperatures of 20°C—Eq. (7), 35°C—Eq. (8), and 50°C—Eq. (9), can be observed in Fig. 5(b) between $\eta/(L_{iv})^{0.30}$ and the unconfined compressive strength (q_u):

$$q_u(kPa) = 3.14x10^7\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad \text{Eq.(7)}$$

$$q_u(kPa) = 6.50x10^7\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad \text{Eq.(8)}$$

$$q_u(kPa) = 7.03x10^7\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \quad \text{Eq.(9)}$$

Examining Figs. 5(a and b) shows that q_t and q_u of the sand-fly ash-lime blends present rather similar trends. Plotting q_t versus q_u data for curing temperatures of 20, 35, and 50°C, a unique relationship between unconfined compressive strength (q_u) and splitting tensile strength (q_t) is observed in Fig. 5(c). This demonstrates that q_t/q_u is a scalar for the studied sand-fly ash-lime blends (q_t/q_u=0.19), being independent of curing temperature, porosity, lime content, or porosity/lime ratio.



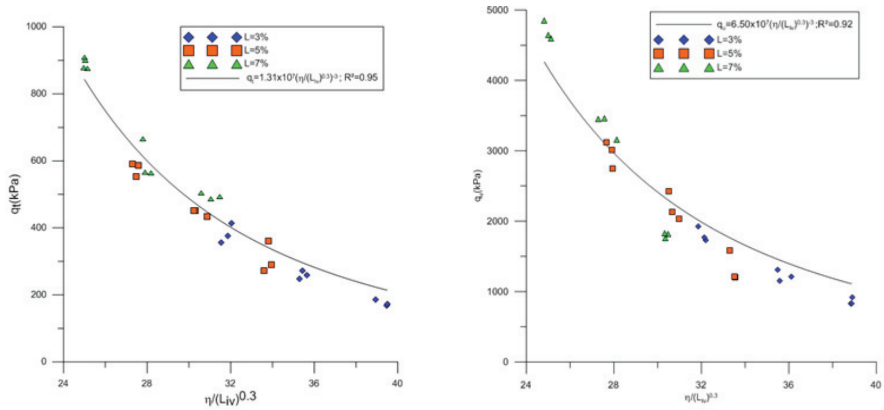
(a) (b)

Figure 3-Variation of porosity/lime ratio (η/L_{iv}) with: (a) splitting tensile strength; (b) unconfined compressive strength for curing temperature of 35°C

Further considerations demonstrate the variation of normalized strength: (1) normalized splitting tensile strength $q_t/[\eta/(L_{iv})^{0.30}]^{-3.0}$[using Eqs. (3)–(6)], and (2) normalized unconfined compressive strength $q_u/[\eta/(L_{iv})^{0.30}]^{-3.0}$ [using Eqs. (7–9)], with curing temperatures (T). Both normalized strengths increase linearly with increasing temperature up to 35°C, when they reach asymptotes, meaning that for a curing period of 28 days, temperatures above 35°C do not cause further increase in strength (meaning that all pozzolanic reactions have finished, at 28 days of curing, under a temperature of 35°C). Besides, between 20 and 35°C unique relationships can be achieved linking the q_t and q_u with η; L_{iv} and T, as presented in Figs. 6(a and b) and in Eqs. (10) (R^2 =0.99) and (11) (R^2 = 0.99), respectively:

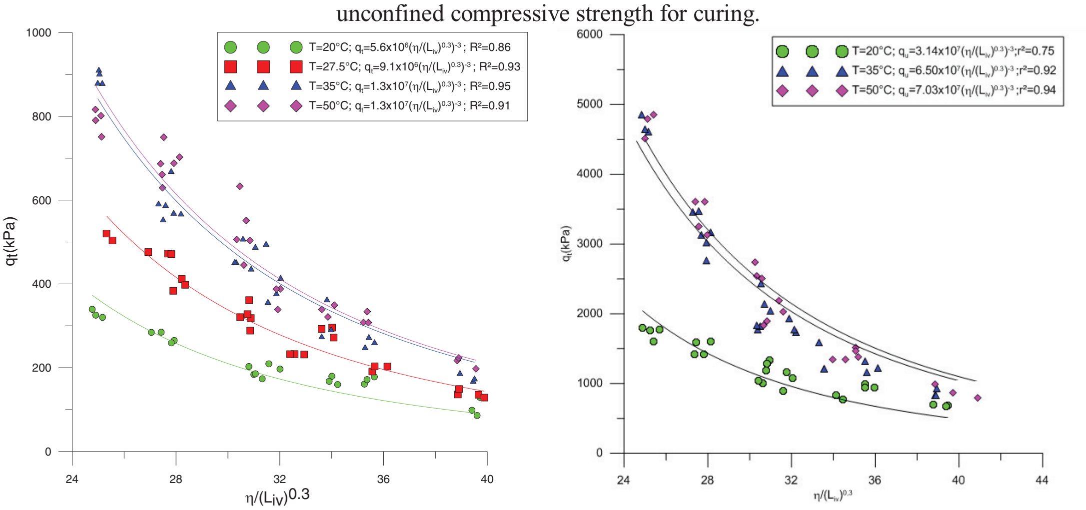
$$q_t(kPa) = \left[0.5x10^6(T) - 4.3x10^6\right]\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \qquad \text{Eq.(10)}$$

$$q_u(kPa) = \left[0.22x10^7(T) - 1.3x10^7\right]\left[\frac{\eta}{(L_{iv})^{0.30}}\right]^{-3.0} \qquad \text{Eq.(11)}$$



(a) (b)

Figure 4- Variation of adjusted porosity/lime ratio $[[\eta/(L_{iv})^{0.30}]^{-3.0}]$ with: (a) splitting tensile strength; (b) unconfined compressive strength for curing.



(a) (b)

Figure 5-Relationships of adjusted porosity/lime ratio $[[\eta/(Liv)^{0.30}]^{-3.0}]$ with: (a) splitting tensile strength (q_t); (b) unconfined compressive strength (q_u) considering distinct curing temperatures (T) of 20°C, (27.5°C—only for q_t), 35, and 50°C.

So, as both q_t and q_u of the sand-fly ash-lime blends increase linearly (both double their values with the increase in the temperature from 20 to 35°C), Eqs. (10) or (11) can be used as dosage relationships for the soil, fly ash and lime studied in the condition studied in this research.

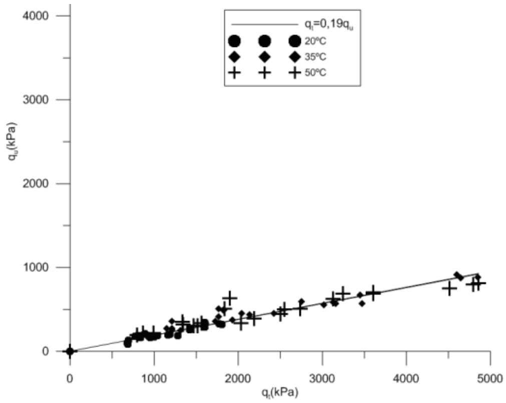
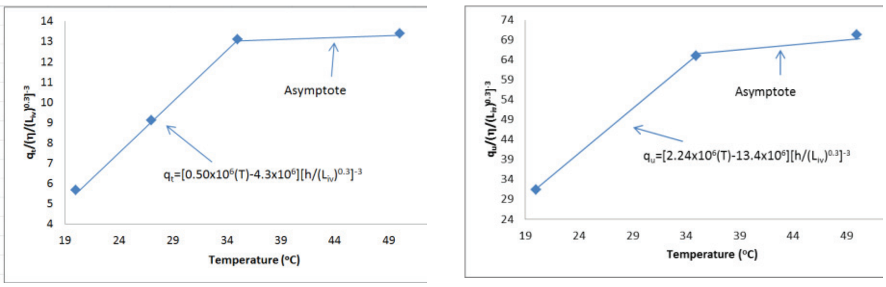


Figure 4 Unique relationship between unconfined compressive strength (q_u) and splitting tensile strength (q_t) considering curing temperatures (T) of 20°C, 35°C e 50°C.



(a) (b)

Figure 6-Variation of: (a) normalized splitting tensile strength; (b) normalized unconfined compressive strength with temperature (T)

4 Conclusions

From the data presented in this manuscript the following conclusions can be drawn:

- The porosity/lime ratio, defined by the porosity of the compacted mixture divided by the volumetric lime content, adjusted by an exponent $[\eta/(L_{iv})^{0.30}]$ has been shown to be, at distinct curing temperatures, an appropriate parameter to evaluate the splitting tensile strength and unconfined compressive strength of sand-coal fly ash-lime blends studied. Plotting q_t versus q_u data for curing temperatures of 20, 35, and 50°C, a unique relationship between them is observed. It can be concluded that q_t/q_u is a scalar for the studied sand-fly ash-lime blends (q_t/q_u=0.19), being independent of curing temperature, porosity, lime content, or porosity/lime ratio.
- For the studied curing time period, the relations $q_t/[\eta/(L_{iv})^{0.30}]^{-3.0}$ versus T and $q_u/[\eta/(L_{iv})^{0.30}]^{-3.0}$ versus T are shown to vary linearly up to a threshold, when asymptotes occur, meaning that higher temperatures do not further enhance strength attributable to extinction of soil-lime-fly ash reactions. Therefore, temperature is seen as an efficient catalyzer for sand-fly ash-lime mixtures up to the threshold.

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